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A Coupled Seismo-Acoustic Simulation Capability FY2014 LDRD Project 14-ER-001 Report

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FY2014 LDRD Project 14-ER-001 Report

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Summary

This report summarizes progress on LDRD project 14-ER-001 “A Coupled Seismo-Acoustic Simulation Capability” during its first year (Fiscal Year 2014). This project involves the development of a coupled seismo-acoustic wave propagation capability that builds on extensive experience in seismic (elastic) wave propagation capabilities using the LLNL-developed codes WPP and SW4. During this first year the problem was formulated and a basic solver for acoustic wave propagation was developed. Importantly, the formulation allows three-dimensional variations in the atmospheric pressure, density and sound speed as well as a (slowly) moving atmosphere, which provides new capability to simulate the geophysical motions from energetic events of interest to LLNL programs. We have met the goals laid out for this first year and are on track to accomplish the goals of the project.

Work Completed in FY2014

This section summarizes the work completed in FY2014. In this first year, effort was focused initially on development of the formulation of the acoustic wave propagation and coupled seismo-acoustic problems. The development was done knowing we would rely heavily on existing capabilities for elastic wave propagation in solid media, following the existing seismic simulations codes WPP and SW4. A system of equations for acoustic wave propagation was derived from the equations of compressible fluid dynamics. Importantly, this formulation allows three-dimensional variations in the atmospheric pressure, density and sound speed as well as a (slowly) moving atmosphere.

We model acoustic waves as small perturbations on top of a given background velocity, pressure and density field, which is assumed to be in static equilibrium. Our formulation allows for spatially varying wind, ambient pressure, and density gradients. It solves the linearized Euler equations of compressible fluid flow (Landau and Lifshitz, 1959) using the ideal gas law as equation of state (Ostashev et al. 2005; Munz et al. 2007). The resulting hyperbolic system consists of 5 partial differential equations for the perturbations of pressure, 3 velocity components, and density. Note that this is a slightly more general system of equations compared with previous approaches, which assume the particle velocities to be small compared to the acoustic wave speed (small Mach number), and neglect the influence of buoyancy and variations in entropy (de Groot-Hedlin et al., 2011). A change of variables was developed such that the governing equations are transformed to symmetric hyperbolic form. This allows an energy estimate for the solution of the symmetrized acoustic system. The energy estimate is the backbone of the summation by parts (SBP) discretization of the acoustic equations. The SBP property allows the energy estimate to be carried over from the continuous equations to the discretized system. This leads to a proof of stability for any high order accurate SBP discretization on a bounded domain with spatially heterogeneous background properties (wind, pressure, and density gradients). Furthermore, the boundary term that appears in the energy estimate indicates the type of boundary condition that must be imposed. When the acoustic equation is solved in isolation (i.e., uncoupled from the solid earth), the product of the normal velocity and pressure must be set to zero on a solid boundary. In the case of coupled seismo-acoustic wave propagation, the boundary term must be matched with the corresponding boundary term from the energy estimate of the elastic wave equation. In this case, we can guarantee that the total energy in the coupled system is conserved if we match the normal traction and normal velocities along a free surface seismo-acoustic interface. We successfully tested this coupling approach on the 1-D acoustic-elastic problem. Furthermore, we have generalized the coupling approach to the full 3-D seismo-acoustic problem.

We developed a sixth order accurate SBP discretization for the system of equations describing acoustic wave propagation. Currently, only Cartesian domains are supported. Inclusion of domains with topography is a milestone for FY15. This basic scheme is non-dissipative and therefore sensitive to modes that are unresolved on the grid, for example due to point forces or rapidly varying background properties. To remove such modes from the numerical solution, we developed a 7^{th} order artificial dissipation scaled by a characteristic decomposition. The resulting scheme can be interpreted as a 6^{th} order upwind SBP method. From classical results for finite difference methods we expect our method to need about 5 grid points per wavelength to give 10 percent accuracy. This should be compared with 20 grid points per wavelength to achieve the same accuracy with a second order accurate method, which currently is used by most acoustic modeling codes (de Groot-Heldin et al. 2008; Ostashev et al. 2005). Compared with a second order method, this means that our method should be able to model waves with about 4 times larger frequency on a grid with the same grid size.

We have implemented an MPI-based parallel code (currently called SAW4) for computing three-dimensional acoustic wave propagation on a Cartesian domain. This code currently implements solid wall boundary conditions on a flat surface and super-grid absorbing far-field layers. It allows for simple heterogeneous background properties. The solver has been verified using the method of manufactured solutions, which tests the stability and order of accuracy when the solution is smooth. An initial implementation of point forcing functions, modeling acoustic sources, has also been accomplished, but more testing is needed. These functions are critical to modeling energetic events, as well as allowing validation against canonical test problems.

As an illustration of the capabilities developed during FY14, we show computed results by our acoustic solver from simulating the 2008 bolide explosion over the US Pacific Northwest. This is the same case as computed in de Groot-Hedlin et al. 2011. Figure 1 shows the computational domain with receiver stations and the location of the bolide explosion, at 27km altitude. Figure 2 shows received signals at the stations for a zero wind atmosphere. The pressures recorded at the difference stations are plotted vs. a reduced time. Figure 3 shows the same computation, but with a realistic wind. The effect of the wind is clearly visible, as well as a second arrival from reflections in the stratospause. The frequency of the source was 0.125 Hz, and the simulation computed the acoustic waves up to time 1500 seconds on a domain of size 500x250x67 km. The computation used approximately 130 million grid points, and ran for 15 minutes on 4096 cores on Vulcan.

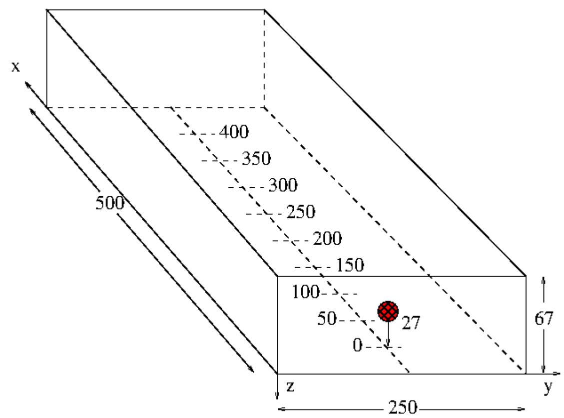

Figure 1. Simulation domain with bolide explosion (red) and stations along the x-axis.

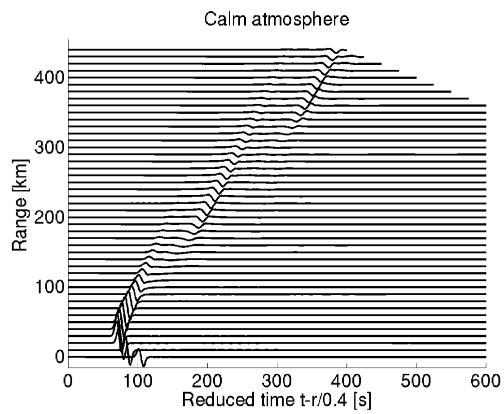

Figure 2. Signals recorded at stations (along y-axis) vs. reduced time, with no wind.

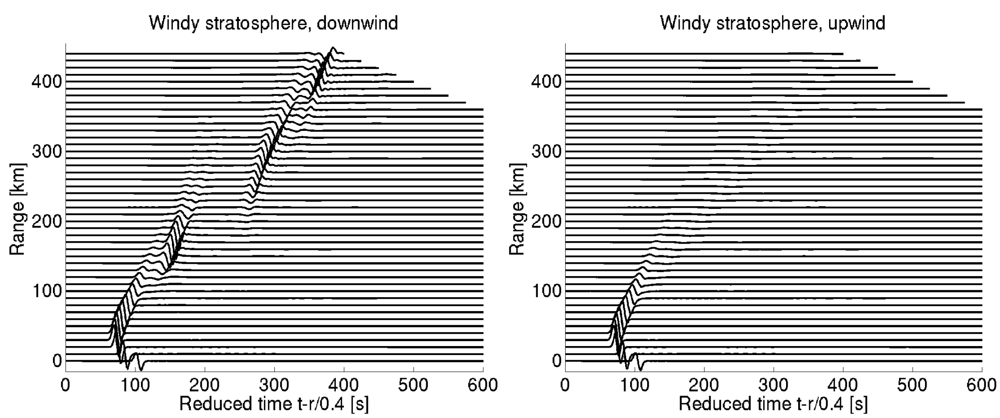

Figure 3, signal recorded at stations with atmospheric wind. Subfigures show downwind of source (left) and upwind of source (right).

Presentations Made in FY2014

This LDRD project supported presentation of our efforts at scientific meetings and partial completion of a journal article. These are listed below:

- Petersson, N.A., B. Sjogreen, and A.J. Rodgers, "A seismo-acoustic infrasound methodology for accurate large scale simulations". Poster presentation. Seismological Society of America annual meeting, Anchorage, AK, LLNL-POST-653841, April 2014.

- Petersson, N.A., B. Sjogreen, and A.J. Rodgers, "Two summation-by-parts finite difference codes for accurate large scale simulations of seismic motion", Poster presentation, Seismological Society of America annual meeting, Anchorage,
- AK, LLNL-POST-653713, April 2014.

- Petersson, N.A., "Summation-by-parts methods for accurate seismo-acoustic wave simulations", Invited oral presentation, 11th International Conference on Theoretical and Computational Acoustics, College Station, TX, LLNL-PRES-651569, March 2014.

- N.A.Petersson and B.Sjogreen, "Super-grid modeling of the elastic wave equation in semi-bounded domains", Comm. Comput. Phys., vol. 16 (2014), pp.913-955.

- Rodgers, A. J. (2013). Infrasound from Buried Seismic Sources in the Presence of Surface Topography, presentation at the 166th Meeting of the Acoustical Society of America and American Geophysical Union Meeting, December 2013, LLNL-PRES-647202

- B.Sjogreen and N.A.Petersson "Summation by parts difference approximations for seismic and seismo-acoustic computations", presentation at the International Conference on Spectral and High Order Methods, Salt Lake City, UT, June 2014, LLNL-PRES-655825

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